Magnetization Reversal in Thin Films*

DONALD O. SMITH†
Lincoln Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received June 15, 1956)

The magnetization reversal of thin films (≈1000 A thick) of 80–20 Permalloy has been studied in a strip transmision line. These films are evaporated onto a heated glass substrate in the presence of an orienting field. Magnetization reversal along the axis of initial orientation takes place in times less than 20 mμsec in any reversing field large enough to overcome the orienting energy. The switching coefficient S_w is defined by $S_w=H_m\tau$, with τ the reversal time and H_m the reversing field. The experiment gives $H_m=1$ oe and $\tau<2\times10^{-8}$ sec, from which $S_w<2\times10^{-8}$ oe-sec. Reversal by rotation of the magnetization as a whole in the plane of the film yields a model which is consistent with the observed reversal times. Preliminary measurements of the initial permeability perpendicular to the orientation axis have been carried out to 2000 Mc/sec and do not yet reveal the expected frequency dispersion of the initial permeability. This is an indication that S_w may be another order of magnitude smaller than reported here.

THE preparation and magnetic properties of thin films (≈1000 A thick) of vacuum-evaporated 80–20 Permalloy have been reported by Blois.[1] When the film is deposited on a heated glass substrate (microscope slide) in the presence of an external magnetic field in the plane of the film, the film develops a preferred magnetic axis in the field direction, becoming a single domain oriented in this direction.

If the uniaxial anisotropy energy in the plane of the film is described by $E_K=K\sin^2\theta$, then simple theory predicts that for a 180° reversing field $>2K/M$, where M is the magnetization, the film should reverse its magnetization by rotation of the entire domain within the plane of the film. This will be realized experimentally if the anisotropy energy is small compared to the energy required to create walls; alternatively, since rotation reversal is expected to be much faster than wall reversal, if a reversing field $>2K/M$ is applied with a rise time short compared to times required for walls to form and move, rotation reversal will be expected to occur.

The switching coefficient S_w has been defined by Menyuk and Goodenough[2] by the expression $(H_m-H_0)\tau=S_w$, with H_m the reversing field, H_0 a threshold field for irreversible flux change ($2K/M$ for rotation reversal), and τ the reversal time. S_w for thin tapes of Mo-Permalloy has an experimental value of 5×10^{-7} oe-sec. The theoretical expression for S_w gives $S_w\propto d/\delta$, with δ a wall thickness and d the distance this wall moves during reversal. For Mo-Permalloy, the theory plus the experimental value of S_w give $d/\delta\approx500$. If reversal takes place by rotation as a single domain, we set $d/\delta=1$, leading to $S_w\approx10^{-9}$ oe-sec.

The switching coefficients for 80–20 Permalloy films as reported by Blois are not much different from those for Mo-Permalloy tapes as reported by Menyuk and Goodenough; however, Conger[3] measured the component of magnetization in the plane of the 80–20 Permalloy films during reversal and obtained results which seemed to indicate that the reversal was actually taking place by rotation. In an attempt to resolve these contradictory results, the reversal of a film made as described by Blois has been studied in the apparatus shown schematically in Fig. 1. The drive pulse has a rise time of 1mμsec and is generated by discharging a coaxial line through a mercury relay. In order to provide for an H field with plane geometry, the pulse is sent down a strip transmission line which is terminated to avoid reflections. A pulse to reset the film after reversal by the fast-rise-time drive pulse is provided by a simple capacitor discharge through a second mercury relay. The pickup loop is balanced to eliminate air coupling as shown in Fig. 1; the film is placed in one arm of the loop with the magnetic axis along the normal to the loop and crosswise in the strip line. Typical film dimensions are 1 cm² by 2000 A thick. The voltage from the pickup loop is displayed on an oscilloscope having a rise time of approximately 20 mμsec.

For drive fields less than a critical value H_0 there is no switching pulse from the film; for any field $>H_0$ the film switches in a time <20 mμsec, as shown by the fact that the switch pulses have the same character as pulses due to imbalance in the air coupling of the two arms of the pickup loop, with a duration determined entirely by

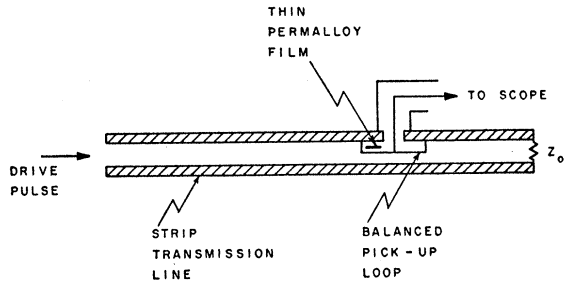

FIG. 1. Schematic representation of apparatus used to study the magnetization reversal of thin films of 80–20 Permalloy.

* The research in this document was supported jointly by the U.S. Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.
† Staff member, Lincoln Laboratory, Massachusetts Institute of Technology.
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[2] N. Menyuk and J. B. Goodenough, J. Appl. Phys. **26**, 8 (1955).
[3] R. L. Conger, Phys. Rev. **98**, 1752 (1955).

the rise time of the viewing scope. The switch pulse amplitude varies linearly with drive pulses $>H_0$; however, the apparent time of reversal does not change proportionally with increased drive, because of the response limitation of the viewing equipment.

In order to define a switching coefficient which can describe these experimental results, we note that the first half of a rotation process is opposed by an effective anisotropy field of $2K/M$, and in the second half it is aided by the same field. Hence the average H_0 in the definition of S_w is zero, and we set $H_m\tau=S_w$. Since reversal first occurs for $H_m=1$ oe, we have from the experimental data $S_w<2\times10^{-8}$ oe-sec.

Since faster scopes are not available at present, the ultimate speed of a rotation reversal can only be estimated by examining the frequency dependence of the initial permeability in the direction perpendicular to the magnetic axis; this permeability is due almost entirely to domain rotation. Using the same apparatus, but with sine wave excitation and heterodyne detection and rotating the film by 90°, the permeability has been studied out to 2000 Mc/sec. Improvements in the apparatus are being made in order to obtain accurate data at higher frequencies, but the relaxation of the permeability with frequency is by no means complete at 2000 Mc/sec, indicating that the reversal time by domain rotation can be expected to be one or two orders of magnitude faster than 20 mμsec. This is in agreement with the previous estimate for the switching coefficient.

These preliminary results suggest that in this experiment magnetic reversal is taking place by domain rotation as evidenced by the speed of the reversal. It is to be expected that under different experimental conditions reversal can take place by wall motion, or by a combination of wall motion and rotation leading to slow reversal times. That walls can exist in these films has been shown by Fowler and Fryer.[4] Walls will be expected to contribute to the switching in several different experimental situations, e.g., (a) if the drive field is not uniform over the area of the film, and (b) if the rise time and duration of the drive pulse are long enough that walls can form and move in fields less than the critical one for domain rotation.

Note added in proof.—Both the theory and the experiments have now been extended to show that rotational switching can take place over a wide range of speeds, depending on the orientation of the magnetic axis with respect to the switching field. The importance of this orientation was first demonstrated experimentally by Olson, Pohm, and Rubens.[5] Thus the results of Conger demonstrating slow rotational switching are completely consistent with the fast rotational switching reported here.

[4] C. A. Fowler, Jr., and E. M. Fryer, Phys. Rev. **100**, 746 (1955).
[5] Olson, Pohm, and Rubens, Armour Symposium on Relaxation in Ferromagnetic Materials, April 4–6 (1956), Armour Research Foundation of Illinois Institute of Technology.

PHYSICAL REVIEW VOLUME 104, NUMBER 5 DECEMBER 1, 1956

Scattering of Electrons by Lattice Vibrations in Nonpolar Crystals*

WALTER A. HARRISON†
University of Illinois, Urbana, Illinois
(Received July 27, 1956)

A theoretical analysis of the scattering of electrons by lattice vibrations in nonpolar crystals is made which permits an estimate of the relative importance of acoustical-mode and optical-mode scattering in monatomic nonmetals. This comparison is achieved by expanding the matrix elements for scattering in powers of the electron wave number. Individual terms are examined in the light of crystal symmetries and the nature of the band minimum associated with the carriers. The order of the first nonvanishing term is obtained in each case. The temperature dependence of the mobility as indicated by these results is compared with that observed in the cases of electrons and holes in silicon and germanium. The observed dependence upon temperature is understandable in terms of the expected relative importance of acoustical- and optical-mode scattering in the cases of holes in silicon and germanium and electrons in germanium. In the case of electrons in silicon, optical modes are not expected to contribute appreciably and the strong temperature dependence must arise from some other mechanism, presumably intervalley scattering. The relation between the results obtained here and those of deformation-potential theory is discussed briefly.

I. INTRODUCTION

ALTHOUGH the scattering of electrons by acoustical vibrations in nonpolar crystals has been studied extensively, there has not been an analysis of the scattering by optical modes which allows for comparison of the two when both may be important. The purpose of this work is to attempt to supply that analysis.

Optical modes occur only in crystals having two or more atoms per unit cell. Since the most important cases are those in which there are two atoms per unit cell and hence a single band of optical modes, the work

* Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics at the University of Illinois.
† Now at General Electric Research Laboratory, Schenectady, New York.